Undergraduate Research on Physically Informed Transmission Line Design

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***Abstract*—Modern power system studies increasingly require transmission grid models that are not only electrically plausible but also physically consistent enough to support resilience and infrastructure-risk analysis. However, in many public synthetic cases, electrical parameters (R, X, B) and physical attributes (tower and conductor types, ratings, line lengths) are assigned largely independently, so thermal limits, impedances, and shunt terms do not always correspond to a realizable line design. This paper proposes a dual-path reconstruction framework that embeds standard transmission line physics and a library of typical ACSR conductors into synthetic models. Depending on which data are deemed more credible, the method treats either the thermal ratings ("Preserve MVA") or the impedance set ("Preserve RXB") as fixed, and then infers ACSR conductor size, bundle configuration, geometric mean radius (GMR), geometric mean distance (GMD), and line length to obtain a physically and electrically consistent design. Case studies on the EPIGRIDS 7k and ACTIVSg 2k Texas bus synthetic cases show that the reconstructed models closely match the original operating characteristics while supplying the additional design detail needed for tower- and weather-aware resilience studies. A validation was also conducted against the 2024 series ERCOT operating case.**

I. Introduction

Publicly available synthetic power grid models have become essential tools for research in grid modernization, renewable integration, and resilience analysis [1]. They enable realistic power flow, contingency, and planning studies without revealing sensitive infrastructure details [2]. In contrast, real utility transmission line data are not always publicly available for research [3], [4]. At the same time, growing renewable penetration, load growth, and more frequent extreme weather events are increasing the need for models that respect underlying physical constraints [5], [6].

A key challenge in both synthetic and real-world transmission modeling is ensuring that electrical and physical parameters are mutually consistent [1], [4], [7]. For many transmission lines, impedances, shunt susceptances, and thermal limits are chosen to match target loading and congestion patterns, while line lengths and conductor choices are derived from geographic data or simple rules [2], [3]. The resulting combinations of (R, X, B), ratings, and lengths are not always explicitly tied to the relationships between line parameters, conductor properties, and geometry documented in standard transmission line references [8]–[11]. These combinations can be difficult to map back to specific physical conductor designs, motivating methods for explicit conductor reconstruction.

Resilience-oriented analyses further require models that expose physically coherent conductor sizes, bundle configurations, and phase spacings so that tower representations and hazard fields can be meaningfully attached [5], [6], [12]. Bridging the gap between published electrical parameters and an explicit ACSR-based line design is therefore a necessary step toward using both synthetic and real systems in these workflows [13]. In this work we focus on two complementary testbeds. EPIGRIDS-Texas is an entirely synthetic 7,336-bus network covering the geographic footprint of Texas, with 345, 230, 138, and 69 kV transmission levels and loads that roughly mimic the population distribution in its footprint, and is designed by the algorithms in [4] to be statistically similar to actual transmission systems while not modeling any actual lines. This makes it a controlled benchmark for methods that operate on publicly available parameter data. ERCOT models, in contrast, reflect actual system topology and operating constraints but may lack uniform coverage of detailed line-design attributes, making them a natural testbed for inferring missing line design information while preserving observed electrical behavior [3], [4].

This paper presents a physically grounded methodology for reconstructing transmission line designs in both synthetic and real grids and for evaluating their consistency with standard ACSR practice. We develop a dual-path parameter correction framework that embeds standard transmission line physics and a library of typical ACSR conductors into network models [7]–[11]. We validate this approach on the EPIGRIDS Texas synthetic system, the Texas 2k synthetic case, and a 2024 ERCOT transmission planning model, demonstrating that the resulting augmented cases supply the line design detail needed for tower- and weather-aware resilience studies while preserving the original operating characteristics. The ERCOT grid was used in partnership with LCRA under an NDA.

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II. Methodology

The reconstruction methodology provides two complementary pathways that differ in which data source is treated as the reference constraint. The choice between pathways depends on the provenance and reliability of the available data:

- Preserve MVA Pathway: Applied when thermal ratings are considered reliable, typically in synthetic grids where MVA limits are assigned based on regional utility standards or in planning cases where ratings have been vetted against operational data. This pathway treats the published MVA as fixed and infers conductor specifications that match those thermal limits.
- Preserve RXB Pathway: Applied when electrical parameters (R, X, B) are considered reliable, typically in real utility grids where impedances have been validated.

To maintain tractability at system scale, the reconstruction assumes a balanced three-phase, 60 Hz system with fully transposed lines and identical subconductors within each bundle [12]. The methodology is limited to overhead ACSR (Aluminum Conductor Steel Reinforced) conductors and does not account for other conductor types such as composite core conductors (e.g., ACCC, ACCR) or underground cables, which may exhibit different thermal and electrical characteristics. The conductor ampacity values used in thermal rating calculations correspond to a single, representative operating condition (typically normal weather with moderate ambient temperature), whereas actual utility ratings often vary seasonally or use real time ambient adjusted values. Published MVA limits in power flow cases may also reflect constraints other than thermal capacity, such as voltage drop, transient stability margins, or right of way clearances. Additionally, each transmission line is modeled with a single, uniform tower geometry and constant GMD along its entire length; in practice, lines along a right of way often employ multiple tower configurations with varying phase spacings. For each voltage level, phase spacing and bundle count are restricted to plausible ranges (e.g., one to four subconductors per phase, within spacing bounds drawn from [10], [11]) so that all evaluated candidate designs remain within typical utility practice.

A. Preserve MVA Pathway

The Preserve MVA approach is used when thermal ratings are considered reliable, often the case when synthetic grids are calibrated against regional utility standards. This pathway treats the original MVA limit as ground truth and selects a physical conductor configuration to match it.

1) Conductor Selection by Thermal Rating: For each transmission line, the algorithm evaluates all conductor-bundle combinations from an ACSR library as in . Each configuration's thermal MVA rating is:

$$S_{\text{cond}} = \sqrt{3} \cdot V \cdot I_{\text{amp}} \cdot N_c \tag{1}$$

where V is line voltage (kV), I_{amp} is conductor ampacity (A), and N_c is the number of bundled subconductors. The algorithm selects the configuration that minimizes the absolute difference from the original MVA limit:

$$\Delta S = |S_{\text{cond}} - S_{\text{orig}}| \tag{2}$$

where S_{orig} is the original MVA limit from the case file.

When multiple configurations yield MVA differences within a 5% tolerance of each other, the algorithm prefers the configuration with fewer bundles. This reflects real-world utility practice, where simpler single conductor or lower bundle designs are favored over more complex bundled configurations when thermal performance is comparable, due to reduced construction complexity, maintenance requirements, and tower loading.

2) Physical Geometry and Electrical Parameters: With the conductor selected, the GMD is assigned from the midpoint of the typical range for the line's voltage class (Table I), and subconductor spacing is set to standard values for the voltage level (e.g., 1.5 ft for 345 kV and above). The electrical parameters R, X, and B are then calculated as outputs using the transmission line equations presented in Section II-B. Critically, the percent deviation between these calculated values and the original parameters serves as a diagnostic metric: low deviation indicates the original case was already physically consistent, while high deviation reveals that the original electrical parameters did not correspond to a realizable conductor design for the given MVA rating.

TABLE I
Typical GMD Ranges by Voltage [4], [7], [9]–[11]

Voltage (kV)	GMD Range (ft)
69	4 – 15
138	8 – 26
230	14 – 35
345	20 – 44
500	31 – 48
765	47 – 66

B. Preserve RXB Pathway

The Preserve RXB approach assumes the original electrical parameters (R, X, B) are ground truth. The objective is to reverse-engineer a physical line design that replicates these values. This method is inspired by [12]. A candidate ACSR conductor is chosen from a standard library [10], [11] such that its rated ampacity meets or exceeds I_{req}, thereby fixing the conductor's physical properties and single-conductor GMR. For bundled conductors, an equivalent bundle GMR GMR_{eq} is computed as

$$\text{GMR}_{\text{eq}} = \begin{cases} \text{GMR}_s, & N_c = 1, \\ \sqrt{\text{GMR}_s \, d_{\text{bundle}}}, & N_c = 2, \\ \left(\text{GMR}_s \, d_{\text{bundle}}^2\right)^{1/3}, & N_c = 3, \\ 1.091 \left(\text{GMR}_s \, d_{\text{bundle}}^3\right)^{1/4}, & N_c = 4, \end{cases} \tag{3}$$

following [7], [9], where N_c is the number of subconductors and d_{bundle} is the bundle spacing. To recover a physically

consistent geometry from the original line parameters, the line length l is first estimated from the original reactance X_{actual} and susceptance B_{actual} using the lossless line model [8], [9],

$$l = \frac{c}{2\pi f}\sqrt{X_{\text{actual}}\, B_{\text{actual}}}, \tag{4}$$

where c is the speed of light and f is the system frequency (60 Hz). The corresponding phase inductance $L_{\text{actual}} = X_{\text{actual}}/(2\pi f)$ is then used to obtain the GMD by inverting the standard inductance formula for a single-circuit line:

$$\text{GMD} = \text{GMR}_{\text{eq}} \exp\left(\frac{L_{\text{actual}}}{l}\,\frac{2\pi}{\mu_0}\right), \tag{5}$$

where μ_0 is the permeability of free space [8], [9]. The resulting GMD is constrained to typical ranges for the given voltage class, as summarized in Table I [4], [7], [9]–[11]. Given the selected conductor, bundle configuration, length l, and GMD, the electrical parameters are recomputed as

$$R_{\text{calc}} = R'_{\text{ac}}\, l, \tag{6}$$

$$X_{\text{calc}} = 2\pi f L = 2\pi f\left[\frac{\mu_0 l}{2\pi}\ln\left(\frac{\text{GMD}}{\text{GMR}_{\text{eq}}}\right)\right], \tag{7}$$

$$B_{\text{calc}} = 2\pi f C = 2\pi f\left[\frac{2\pi\epsilon_0 l}{\ln\left(\frac{\text{GMD}}{\text{GMR}_{\text{eq}}}\right)}\right], \tag{8}$$

where R'_{ac} is the AC resistance per unit length and ϵ_0 is the permittivity of free space [8], [9]. These yield a physically grounded triplet $(R_{\text{calc}}, X_{\text{calc}}, B_{\text{calc}})$ for the candidate design. To assess the match to the original line, percent deviations e_R, e_X, e_B between $(R_{\text{calc}}, X_{\text{calc}}, B_{\text{calc}})$ and the original $(R_{\text{actual}}, X_{\text{actual}}, B_{\text{actual}})$ are combined into a weighted deviation metric

$$E = w_R|e_R| + w_X|e_X| + w_B|e_B|, \tag{9}$$

with w_X purposefully chosen larger than w_R and w_B to prioritize matching line reactance, since X largely governs power transfer and congestion patterns in high-voltage networks, especially in this paper's DC power flow based overload resolution. Different error weighting schemes may yield different conductor selections. Among all feasible candidate designs that satisfy I_{req}, the one minimizing E is selected. The resulting $(R_{\text{calc}}, X_{\text{calc}}, B_{\text{calc}})$ and the original MVA rating define the corrected line. The associated ampacity and voltage level of the selected design then yield an implied MVA rating for the line.

C. System-Level Application and Overload Resolution

For synthetic cases, the newly designed lines must not cause any overloads to the final network. Starting from the original synthetic case, a DC power flow is solved using Easy SimAuto (ESA) [14] to identify branches whose MW flows exceed their current thermal ratings. The method for resolving overloads depends on which pathway is employed.

1) MVA-Based Overload Resolution: When using the Preserve MVA Pathway, the algorithm first selects the conductor configuration with the closest MVA rating to the original (i.e., minimum ΔS). Since this configuration closely matches the original thermal rating, it typically satisfies the DC power flow. If the selected configuration results in a thermal violation, the algorithm iteratively selects the next-closest MVA rating from the ACSR conductor table until the overload is resolved. This approach leverages the discrete jumps between standard ACSR ratings to provide thermal headroom as needed. If no feasible conductor configuration can resolve the overload, the line is flagged for more substantial network reinforcement.

For each upgraded line, the Preserve MVA Pathway is executed with the new target rating to obtain the corresponding conductor and bundle configuration; the updated $(R_{\text{calc}}, X_{\text{calc}}, B_{\text{calc}})$ and rating are written back to the case, and DC power flow is recomputed.

2) RXB-Based Overload Resolution: When using the Preserve RXB Pathway, the original electrical parameters must be preserved while resolving thermal violations. For each overloaded line, a new target rating S_{target} is defined by applying a modest safety margin m to the observed flow P_{flow}:

$$S_{\text{target}} = (1+m)\, P_{\text{flow}}. \tag{10}$$

The margin is increased gradually (e.g., by 1 percentage point per iteration up to a cap) to avoid large, abrupt changes in line impedances and the resulting power-flow redistributions [2]. The algorithm then searches for the best conductor and geometric combination (bundling, GMD, GMR) that is close to the original (R, X, B) values while satisfying the updated thermal requirement. The updated rating is written back to the case, and DC power flow is recomputed.

3) Convergence and Termination: At each iteration, deviations are measured relative to the original system file: the per-line deviation E quantifies how far each reconstructed line has moved from its initial electrical parameters, and aggregate statistics describe the overall system deviation. The process terminates when (i) no lines are overloaded under the reconstructed ratings, (ii) for MVA-based resolution, all overloaded lines have been upgraded to the maximum available conductor rating, or for RXB-based resolution, the cumulative margin on any line reaches a predefined limit, or (iii) a maximum number of iterations is reached. Lines that cannot be brought within limits are flagged as candidates for more substantial network reinforcements (e.g., new circuits or voltage upgrades), which are outside the scope of this study.

The final output is a system-wide set of ACSR conductor choices, bundle configurations, line lengths, and (R, X, B) values that is both physically consistent and free of thermal overloads under the target operating conditions. The ERCOT Texas grid case being a real grid, it is already functional and operates with robust design schemes. Therefore, a simple ACSR optimization assignment is conducted and compared to the real grid's R, X, and B parameters in order to evaluate the algorithm's performance.

III. Results

The Preserve MVA and Preserve RXB approaches were tested on three test cases: 2024 series ERCOT (real transmission planning case), EPIGRIDS Texas 7k (synthetic case) [4], and Texas 2k Series 25 (synthetic case) [1]. Tables II–IV present deviation statistics for both pathways. Median deviation and number (%) lines with parameter deviations within 20% deviation are reported. Median statistics are used instead of mean to reduce sensitivity to extreme outliers, which are analyzed in Section IV.

A. Preserve MVA Pathway

The Preserve MVA pathway achieved low thermal rating deviations across all test cases. Median MVA deviation ranged from 0.407% (Texas 2k) to 1.299% (ERCOT), with 91.0–99.1% of branches within 20% deviation. Figure 2 shows 94.9% of Texas 2k branches concentrated in the 0–5% bin.

Electrical parameter deviations were higher. Resistance showed median deviations of 3.2% (EPIGRIDS), 26.6% (Texas 2k), and 30.1% (ERCOT). Reactance and susceptance ranged from 4.8–17.8% and 5.0–15.1% respectively (Figure 1). EPIGRIDS performed best with 75.9% of branches within 20% for R and over 97% for X and B.

TABLE II
2024 SERIES ERCOT

	Preserve MVA		**Preserve RXB**	
Quantity	**Median**	**Lines≤20%**	**Median**	**Lines≤20%**
$R_{\text{deviation}}$	30.1%	36.3%	2.7%	86.5%
$B_{\text{deviation}}$	5.7%	75.4%	0.4%	92.4%
$X_{\text{deviation}}$	5.7%	75.8%	0.4%	88.1%
$\text{MVA}_{\text{deviation}}$	1.3%	91.0%	28.7%	43.2%

TABLE III
EPIGRIDS TEXAS 7K

	Preserve MVA		**Preserve RXB**	
Quantity	**Median**	**Lines≤20%**	**Median**	**Lines≤20%**
$R_{\text{deviation}}$	3.2%	75.9%	2.7%	77.2%
$B_{\text{deviation}}$	5.0%	98.2%	0.1%	69.9%
$X_{\text{deviation}}$	4.8%	97.6%	0.1%	100.0%
$\text{MVA}_{\text{deviation}}$	1.1%	75.8%	3.6%	51.2%

TABLE IV
TEXAS 2K SERIES 25 SUMMER PEAK

	Preserve MVA		**Preserve RXB**	
Quantity	**Median**	**Lines≤20%**	**Median**	**Lines≤20%**
$R_{\text{deviation}}$	26.6%	43.4%	1.4%	99.0%
$B_{\text{deviation}}$	15.1%	64.1%	0.2%	63.9%
$X_{\text{deviation}}$	17.8%	59.1%	0.1%	87.6%
$\text{MVA}_{\text{deviation}}$	0.4%	99.1%	9.0%	62.4%

B. Preserve RXB Pathway

The Preserve RXB pathway achieved very low electrical parameter deviations. Median reactance deviation ranged from 0.1% (EPIGRIDS) to 0.4% (ERCOT), with 87.6–100% of branches within 20%. Susceptance showed 0.1–0.4% median deviation (63.9–92.4% within 20%). Resistance had 1.4–2.7% median deviation with 77.2–99.0% within 20%. Figure 3 shows Texas 2k deviation distributions concentrated in the lowest bins.

Thermal rating deviations increased as MVA became an output. Median MVA deviation ranged from 3.6% (EPIGRIDS) to 9.0% (Texas 2k), with 51.2–62.4% within 20% (Figure 4). EPIGRIDS achieved 100% of branches within 20% reactance deviation while maintaining 51.2% within 20% MVA deviation.

C. Comparative Performance Across Cases

Across all three test cases, a consistent tradeoff emerged between the two pathways. Preserve MVA pathway consistently minimized thermal rating deviation at the expense of electrical parameters, while Preserve RXB minimized R, X, B deviation at the expense of MVA rating. Texas 2k showed the most extreme tradeoff, with Preserve RXB achieving 99.0% of branches within 20% resistance deviation but only 62.4% within 20% MVA deviation. EPIGRIDS demonstrated the smallest tradeoff magnitude, with both pathways achieving over 75% of branches within 20% deviation for most parameters. This is expected for electrically and physically uncoupled line parameters.

The histograms in Figures 1–4 visually demonstrate the fundamental pathway tradeoff. For Preserve RXB (Figures 1–2), electrical parameters show exceptional concentration: 95.8% of resistance deviations fall within 0–5%, with reactance (80.7%) and susceptance (55.6%) similarly clustered in the lowest bin. However, MVA deviations spread more broadly, with only 39.0% below 5% and a secondary peak at 5–10% (12.9%). The Preserve MVA pathway (Figures 3–4) exhibits the inverse pattern: MVA deviations achieve tight concentration with 94.9% in the 0–5% bin, while electrical parameters distribute more widely. These distributions confirm that each pathway successfully optimizes its target parameter set—Preserve RXB for (R, X, B) and Preserve MVA for thermal rating—while accepting controlled variation in the complementary parameters.

IV. Discussion

The ERCOT grid reflects actual transmission line parameters. In the real case, the relatively small set of outlier lines with large R/X/B percentage deviations are not random numerical failures but arise where the original branch parameters are structurally inconsistent with ACSR-based physical models. These outliers cluster in specific voltage–conductor combinations, most notably 69–138 kV lines labeled as "Falcon" conductors. Table V shows that Falcon outlier lines exhibit simultaneously lower resistance (56–61% lower) and reactance (61–71% lower) but higher susceptance (6–256%

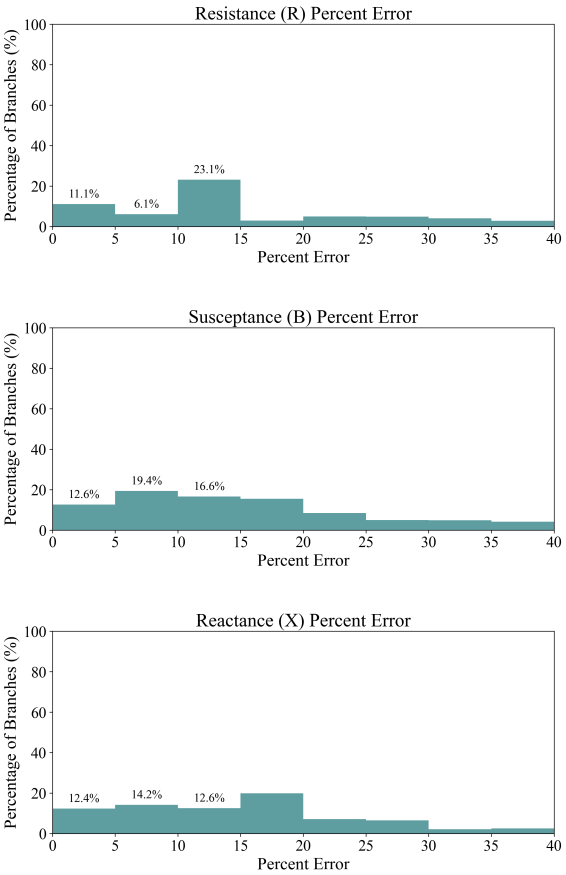

Fig. 1. Texas2k: RXB deviation for Preserve MVA pathway.

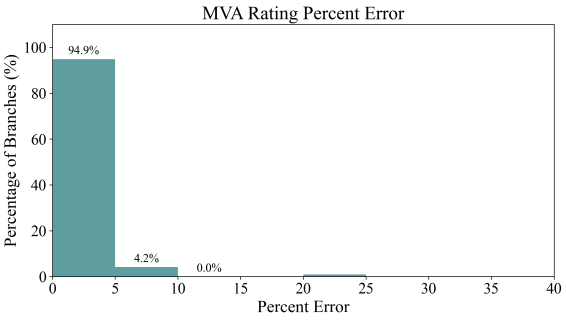

Fig. 2. Texas2k: MVA deviation for Preserve MVA pathway.

TABLE V
ERCOT FALCON LINE PARAMETERS: NORMAL VS. OUTLIER

Voltage	**Type**	**Count**	R **(pu)**	X **(pu)**	B **(pu)**
69 kV	Normal	14	0.0028	0.0302	0.00073
	Outlier	24	0.0011	0.0088	0.00260
	Change		-61%	-71%	$+256\%$
138 kV	Normal	857	0.0008	0.0083	0.00341
	Outlier	601	0.0004	0.0032	0.00363
	Change		-56%	-61%	$+6\%$

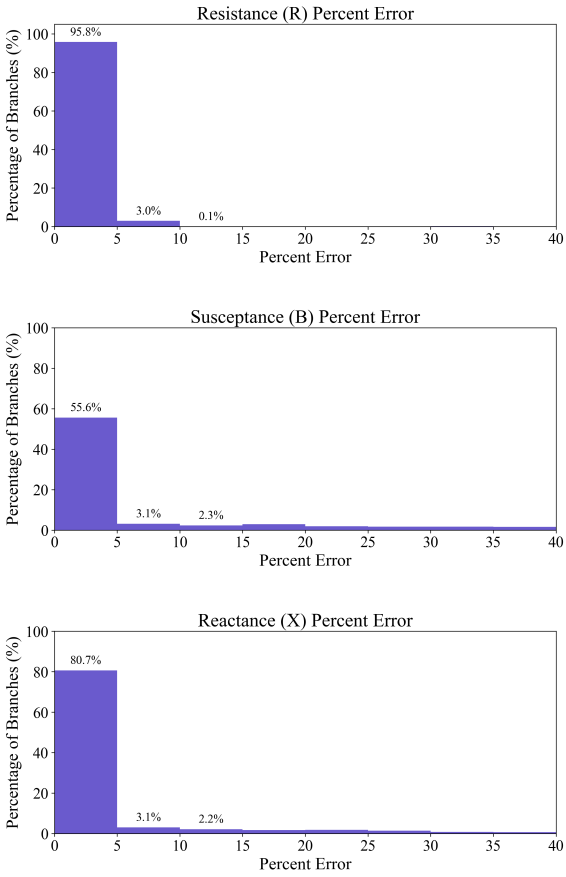

Fig. 3. Texas2k: RXB deviation for Preserve RXB pathway.

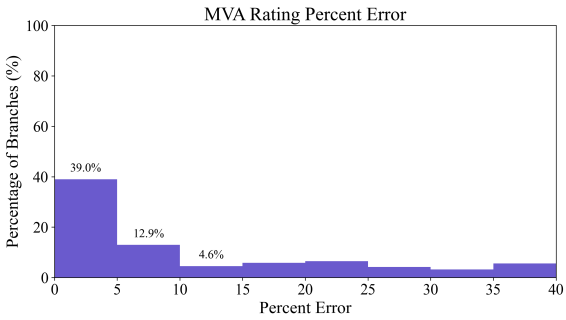

Fig. 4. Texas2k: MVA deviation for Preserve RXB pathway.

higher) compared to normal Falcon lines at the same voltage levels. This pattern is physically impossible to achieve with overhead ACSR conductors, as it would require a line to be simultaneously short (to achieve low series impedance) and long (to accumulate high shunt capacitance). This characteristic signature indicates these lines are likely underground cables, which exhibit precisely this parameter combination due to superior thermal management (lower R), close conductor spacing in cable sheaths (lower X), and high dielectric constant of insulation materials (much higher B). Because the Preserve RXB pathway attempts to match these electrical characteristics using only overhead ACSR conductor options, no feasible

ACSR configuration can replicate this pattern, forcing the optimizer into solutions that match one or two parameters while producing large deviations in the third. Expanding the conductor selection database to include underground cable models and composite core conductors (ACCC, ACCR) would enable accurate reconstruction of these line types.

EPIGRIDS cases use statistical sampling but follow a structured, physically informed approach [4]. These models rely on real conductor data to guide their creation. Critically, transmission line parameters R, X, and B are calculated using standard transmission line equations rather than sampled independently. This physics-based assignment explains the low deviations observed in EPIGRIDS results, particularly the excellent reactance and susceptance matching.

The strong performance on both EPIGRIDS and ERCOT suggests the method is robust. EPIGRIDS, with its physics-based parameter assignment, and ERCOT, representing an actual utility grid, serve as validation benchmarks for the methodology. Specifically, the Preserve MVA approach achieved low MVA deviations (median 1.1-1.3% for EPIGRIDS and ERCOT) while the Preserve RXB approach achieved low electrical parameter deviations (median X deviation of 0.1-0.4%, B deviation of 0.1-0.4%), demonstrating that each pathway successfully optimizes its target parameters when applied to physically consistent or real-world systems.

However, the algorithm showed significantly higher deviations for both pathways on Texas 2k, reflecting the limitations of the design assumptions when applied to synthetic cases with independently sampled electrical and thermal parameters. This calls for a reinforcement of the current assumptions and expansion of the conductor choices in order to accommodate different types of synthetic cases.

The methodology successfully reconstructed ACSR-based transmission line equivalents that respect the design constants across all three cases for each pathway (R,X,B vs thermal), with performance differences reflecting the degree to which each case's original parameters align with the design assumptions.

V. Conclusion

This paper introduced a dual-path methodology for reconstructing physical conductor designs in synthetic power system models through physically informed transmission line design. Two complementary approaches (Preserve MVA and Preserve RXB) systematically infer conductor specifications using established transmission line theory and standard ACSR conductor libraries. Validation across multiple test cases, including EPIGRIDS Texas 7k and Texas 2k Series 25, followed by testing on the 2024 ERCOT planning case (a real utility grid), confirmed the accuracy of the proposed methodology.

The current methodology assumes overhead ACSR conductors, uniform tower geometry per line segment, balanced three-phase transmission lines, and uses DC power flow for overload resolution. The results reveal several priorities for future work. Most critically, expanding the conductor library to include composite core conductors (ACCC, ACCR) and underground cables would improve reconstruction accuracy on real utility grids, as evidenced by ERCOT outliers clustering in lines likely using non-ACSR designs. Second, investigating segmented line models with variable GMD would better capture real transmission corridors with multiple tower configurations. Additional enhancements include validation under AC optimal power flow, extension to transformers and substation equipment, and region-specific calibration of conductor and tower selections based on utility practices documented in FERC Form 1 data.

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